RESISTANCE OF WEEDS TO HERBICIDES

HOMER M. LEBARON
SENIOR RESEARCH FELLOW

BIOCHEMISTRY
CIBA-GEIGY CORPORATION
GREENSBORO, N.C.

PRESENTED TO THE

ILLINOIS CUSTOM SPRAY OPERATORS
TRAINING SCHOOL

UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

JANUARY 8, 1986

To present a comprehensive and accurate review on the current status and the future probabilities of herbicide resistance in weeds, we need to understand a few basic facts. The first one I will state as: "There never has been and never will be an ideal and flawless pesticide." This does not mean that no pesticide will do a perfect job in a given population of one or more pests, or that there is anything really wrong with every pesticide. It is the nature of the pest that imposes the limitations. Neither has there ever been nor ever will be a perfect tool of any kind that will permanently eradicate all pests, at least not before the Millennium arrives. Pests always have and will continue to evolve in order to survive. Their biological flexibility, ecological adaptability and evolution have been recognized as laws or conditions of nature for a long time. The ability of animals and plants to compensate for adverse environmental conditions is remarkable.

Another basic fact is that it makes no difference whether the control method is chemical, mechanical, by plant breeding or some other type of influence; the pest will tend to select for survival. Many assume that pest resistance to pesticides is a phenomenon born from the heavy use of modern effective and specific organic chemicals. Actually, the first occurrence of resistance to a pesticide was reported in Aspidiotus perniciosus (San Jose scale) toward lime sulfur more than 75 years ago. Furthermore, an analogous process occurs when crops and animals are bred with built-in genetic resistance to destructive pests. When confronted with a resistant host, the pest eventually evolves into a new race or strain with counter-resistance or virulence. Thus, many resistant crops and animals do not remain resistant to pests indefinitely.

It could be said with much truth that one of our major problems is that we have succeeded too well. The advent of modern organic chemicals as tools to help human beings tip the balance of nature in their favor was heralded with great success and even greater expectations. I remember some of my colleagues in the 1950s and early '60s predicting, as we saw with great enthusiasm the high degree of weed control (almost total) and crop selectivity from various new types of herbicides, that the farmer could now do away with his hoe and tillage equipment. Some weed scientists even worried that our chemical inventions were so marvelous that

we might solve all weed problems and have no job security. Certainly, the wide use of these very effective pesticides with more selective and specific modes of action has contributed to the rapidly increasing pesticide resistance problems. But this is as much a confirmation on the high levels of activity and value of the pesticides as it is on the adaptability of the pest.

In spite of the occurrence of resistance to pesticides and other limitations or problems associated with their use, no one who understands the adverse consequences to humanity in its present numbers can seriously recommend that chemicals be immediately replaced by alternative means of pest control. The net effect of pesticides, as with drugs, has been an increasing life expectancy with medicines and an increasing food production with pesticides. Chemical pesticides must certainly be a major and increasing part of the agricultural technology in the decades ahead, which will be needed to provide the constantly greater supply of food, fiber and shelter, with greater cost effectiveness. But we must not become complacent, discard other means of pest control, or depend too much on pesticides alone. Herbicide resistance is acting as a self-imposed limiting system of nature. Nature sets the rules. We have to be just as flexible or we lose.

Some scientists predicted or speculated long ago that resistance would develop in weeds to herbicides. Harper, in 1956, was the first to seriously consider that weeds would become resistant, presenting serious problems. His assumptions were based on the current theories and preliminary data from other biological systems, but he had no firm foundation in plant-herbicide studies. By coincidence, his paper was presented about the time atrazine was first tested as a herbicide, but prior to its commercial introduction.

Another basic fact is that resistant weeds are often visually undistinguishable from the more common biotypes that are highly sensitive to particular herbicides. These biotypes were not known to be present or different in any way prior to the introduction of the herbicide(s). More important, they may never have developed into noticeable weed problems if it were not for the new selective pressure provided by repeated use of a particular herbicide or class of herbicides.

The discovery of triazine resistant common groundsel in western Washington in the late 1960s, and the subsequent widespread and frequent occurrence of other triazine resistant weeds over the past 15 years, have made triazine herbicide resistance the best known and most studied such phenomenon. Triazine resistance has also been of greatest interest because of the importance and extensive use of this group of herbicides. However, it was not the first. There have been cases of intraspecific resistance to 2,4-D, dalapon, and other herbicides, and many examples of

evolution toward herbicide tolerance. If other single target site residual herbicides (e.g., diuron) were used so extensively and continuously, they would have almost certainly led to resistant biotypes.

Although weeds have taken longer to evolve herbicide resistance compared to insect pests and pathogens, at the present time, according to my count, 48 species of weeds (35 broadleafs and 13 grasses) which were previously susceptible are known to have developed resistance to triazine herbicides somewhere in the world. Only 18 of these resistant biotypes have been found in the U.S., but one or more of the resistant biotypes have invaded 30 states, four provinces of Canada and 11 other countries. The confirmed triazine resistant weed species and their distribution are presented in Tables 1 and 2. As you will note, only one weed species has, to my knowledge, developed resistance to atrazine in Illinois. That is a biotype of smooth pigweed (Amaranthus hybridus), which has appeared in a localized and small area of White County in southeastern Illinois following a long history of continuous corn and atrazine use.

There is also an increasing number of weeds which have evolved resistance to other types or classes of herbicides, including paraquat, 2,4-D, trifluralin, diuron, diclofop methyl and pyrazon. The weed species which have developed resistance to these herbicides and their distribution, to my knowledge, are presented in Table 3. None of these have appeared in Illinois. A few of these biotypes have not as yet been adequately researched and confirmed. There have been many other reports of nonperformance or claims of resistance which are not listed due to lack of evidence. It is also important when discussing herbicide resistance to differentiate between intraspecific resistance and interspecific or intraspecific tolerance.

In addition to the facts or general principles already stressed, a number of other characteristics of weeds and herbicide resistance are important in considering the best strategy for avoiding their occurrence or managing these and other herbicide resistant weeds once they have developed. While most are based on experiences with and are characteristic of triazine resistant weeds, they are appropriate regardless of the herbicide or weed involved. These may be summarized as follows:

1. Weeds normally require the full growing season to reproduce and often complete one life cycle per year.

2. Weeds do not move about as freely as do insects and disease pathogens.

3. Herbicide resistance has occurred mostly in areas where the same herbicides have been used alone and repeatedly for several years, especially where little or no tillage has been used.

4. Cultivation or other tillage tends to delay or prevent resistant weeds from developing. On the other hand, the trend toward conservation tillage systems reduces alternate weed control options, increasing probabilities of resistant weeds.

5. Crop rotations, which usually result in the use of different herbicides, avoid or delay the development of herbicide resistance.

6. Any resistant weeds that develop will be diluted and competed against by all the soil banks of normal susceptible weed seed.

7. Once resistant plants develop and infest an area with resistant seeds, this source of resistant seed may never be eradicated, even though they can be readily controlled by other means.

8. Where herbicide resistance evolves, a very low frequency of the resistant biotype was likely present among the species population when the problem herbicide was first applied.

9. Resistant weeds are likely to be less competitive compared to susceptible biotypes of the same species.

10. Species that have developed resistance were normally very sensitive and easy to control with these herbicides prior to occurrence of resistant biotypes. (Resistance must not be mistaken for tolerance, which is very common but quite a different phenomenon.)

11. Resistance is generally absolute (e.g., no effect at extremely high rates of herbicide).

12. Biotypes resistant to a herbicide have been resistant to all herbicides within the same class.

13. There are related, though usually lower, degrees of resistance or tolerance to other herbicides having a similar mode of action (e.g., photosynthetic inhibitors).

14. Resistant biotypes seem to have an even greater degree of sensitivity than the susceptible biotypes to herbicides having other modes of action.

15. There is no evidence that the herbicides were a direct cause of resistance, or that they had any mutation effect on the natural susceptible population.

16. All cases of triazine resistance are maternally inherited and, thus, not transmitted by pollen.

17. Other agronomic and ecological factors interact with herbicides to influence the occurrence and rate of resistance.

For these and other reasons, herbicide resistant weeds should be manageable or retained within a reasonable limit. In the U.S., the total area of land or crops infested with triazine-resistant weeds is still relatively small and does not seem to be expanding rapidly. In most areas of the U.S. where triazine resistant weeds have occurred, it has not even been necessary or desirable to cease using the triazine herbicide of choice, due to the many susceptible weeds that are still usually prevalent. However, in Illinois as well as in all areas, with the first invasion of resistant weeds, prompt action is essential in order to avoid serious and permanent problems. Preventive action to avoid herbicide resistant weeds from developing in the first place is the best strategy. It is virtually essential in all cases of herbicide resistance to have other classes or types of herbicides (with alternate sites and modes of action) available.

Herbicides which have been used successfully in combination or alternating with atrazine for control of triazine resistant weeds include metolachlor (Dual), alachlor (Lasso), pendimethalin (Prowl), bromofenoxim (Faneron), dicamba (Banvel), 2,4-D, butylate (Sutan), EPTC (Eptam), linuron (Lorox), paraquat and pyridate (Fenpyrate). Cultivation and other non-chemical weed control systems have also been very helpful in many cases.

From our past experience and research, and based on our knowledge of herbicide modes of action and other characteristics, we are able to predict or project, at least with cautious confidence, which herbicides may have a higher risk for resistance. There will likely always be wide margins for error due to uncertainty about genetic variability of weeds, the primary site or mode of action is not known for many herbicides, the nature and possibilities of cross-resistance between classes of herbicides are poorly understood, and other factors which have not been adequately researched.

In general, we can say that the following characteristics of herbicides will contribute to a high risk for resistance, approximately in order of importance:

1. A single target site and specific mode of action.

2. Extremely active and effective in killing a wide range of weed species.

3. Provides long soil residual and season-long control of germinating weeds.

4. Applied frequently and over several growing seasons without rotating, alternating, or combining with other types of herbicides.

Based on these criteria and our experience to date, I have listed some of the more common herbicides as to their risk for resistance in Tables 4 and 5.

Within the past 10 years, much excellent research has been done on the mechanism of resistance and plant selectivity to the triazine herbicides. This has not only given us a good understanding about how and why herbicide-resistant weed biotypes develop, but our fundamental knowledge of the biochemical process of photosynthesis, the structure and function of the essential proteins involved, and the binding site and mode of action of photosynthetic inhibitors (e.g., herbicides) have all been greatly enhanced, using triazine-resistant weeds as models. With this great advance in scientific information, much of which was started and is still continuing here at the University of Illinois, and other recent developments in modern biotechnology, there are many researchers who are now developing herbicide-resistant crops.

The application of conventional genetics and plant breeding has led to commercial varieties of triazine-resistant rape being grown in Canada, in which the characteristic of resistance was transferred from a closely related weed (wild mustard) to the crop. Genetic engineering and other tools of biotechnology have now made it possible to manipulate genes, enzymes and other characteristics of plants to "create" crops resistant to a wide range of herbicides. These will be coming on the market for experimental and commercial use within the next few years.

In summary, I would list the following as major factors for you to consider in avoiding or managing herbicide-resistant weeds:

a. Do not depend upon one herbicide for total weed control, especially if it is a single site of action herbicide with some history or prediction of resistance.

b. Do not use higher rates of residual herbicides or more frequent applications of postemergence and short residual herbicides than needed.

c. Rotate crops which will tend to reduce the favorable conditions for the problem weed(s), including different herbicides and weed control practices.

d. Where possible, use combinations, rotations or sequential and alternating treatments involving herbicides from different classes or modes of action.

e. It is far better and easier to avoid resistant weeds than to eradicate or control them after they develop, go to seed, and infest an area.

f. Minimum or no-till systems will tend to encourage resistant weed problems. Combinations with or subsequent applications of a new postemergence herbicide (e.g., sethoxydim (Poast), acifluorfen (Blazer), etc.) will be especially needed where tillage and alternate control systems are reduced.

Table 1

DISTRIBUTION OF TRIAZINE-RESISTANT DICOT (BROADLEAF) WEEDS
(as of January, 1986)

	Genera	Species	Common Name	Year Found	Location
1.	Abutilon	theophrastis	velvetleaf	1984	Maryland
				1984	Hungary
2.	Amaranthus	arenicola	sandhills amaranth	1977	Colorado
3.	Amaranthus	blitoides	prostrate pigweed	1983	Israel
4.	Amaranthus	bouchonii		1981	France
				1983	Switzerland
5.	Amaranthus	cruentus	redshank or Italian amaranth	1978	Italy
6.	Amaranthus	deflexus	spreading amaranth	1982	France
7.	Amaranthus	hybridus	smooth pigweed	1972	Maryland
				1976	Virginia
				1977	Delaware
				1978	New York
				1978	Massachusetts
				1978	Pennsylvania
				1979	Switzerland
				1980	Connecticut
				1980	France
				1981	West Virginia
				1982	Illinois
				1984	Maine
				1985	New Jersey
8.	Amaranthus	lividus	livid amaranth	1978	Switzerland
				1981	France
9.	Amaranthus	powellii	green pigweed	1968	Washington
				1970	Oregon
				1975	Ontario
10.	Amaranthus	retroflexus	redroot pigweed	1973	Austria
				1977	France
				1978	Hungary
				1978	Switzerland
				1979	Ontario
				1980	Connecticut
				1981	Michigan
				1981	Ohio
				1982	New York
				1983	Indiana

	Genera	Species	Common Name	Year Found	Location
11.	Ambrosia	artemisiifolia	common ragweed	1975	Ontario
				1984	Pennsylvania
12.	Arenaria	serpyllifolia	thymeleaf sandwort	1981	France
13.	Atriplex	patula	spreading orache	1975	Switzerland
				1978	West Germany
14.	Bidens	tripartita	bur beggarticks	1976	Austria
15.	Brassica	campestris	birdsrape mustard	1978	Quebec
16.	Chenopodium	album	common lambsquarters	1970	Ontario
				1973	Austria
				1973	France
				1973	Switzerland
				1973	Washington
				1976	West Germany
				1977	New York
				1978	Nova Scotia
				1978	Wisconsin
				1979	Belgium
				1979	Virginia
				1980	Hungary
				1980	Michigan
				1980	Netherlands
				1981	Ohio
				1981	New Zealand
				1982	Maryland
				1982	Minnesota
				1983	West Virginia
				1983	Rhode Island
				1983	Pennsylvania
				1983	Massachusetts
				1983	Connecticut
				1984	Maine
17.	Chenopodium	ficifolium	figleaved goosefoot	1977	West Germany
				1983	Switzerland
18.	Chenopodium	missouriense	lambsquarter	1978	Pennsylvania
19.	Chenopodium	polyspermum	manyseeded goosefoot	1979	Switzerland
				1980	Austria
				1980	France
20.	Chenopodium	strictum	lateflowering goosefoot	1978	Ontario

	Genera Species	Common Name	Year Found	Location
21.	Conyza (or Erigeron) canadensis	horseweed	1978	Switzerland
			1981	France
			1981	Hungary
22.	Epilobium tetragonum	square-stalked willow herb	1981	France
23.	Galinsoga ciliata	hairy galinsoga	1980	West Germany
24.	Kochia scoparia	kochia	1976	Idaho
			1976	Iowa
			1976	Nebraska
			1976	Utah
			1977	Colorado
			1977	Kansas
			1977	Oregon
			1978	Oklahoma
			1978	Wyoming
			1979	Montana
			1980	Texas
			1980	Washington
			1984	California
25.	Matricaria matricarioides	pineappleweed (or rayless mayweed)	1984	England
26.	Physalis longifolia	longleaf groundcherry	1984	Pennsylvania
27.	Polygonum (or Fallopia) convolvulus	wild buckwheat	1977	Austria
			1984	Pennsylvania
28.	Polygonum lapathifolium	pale smartweed	1976	France
29.	Polygonum persicaria	ladysthumb	1978	France
30.	Senecio vulgaris	common groundsel	1968	Washington
			1973	Oregon
			1976	California
			1978	British Columbia
			1981	England
			1981	France
			1981	Switzerland
			1983	West Germany
			1984	Hungary

	Genera Species	Common Name	Year Found	Location
31.	Sinapis arvensis	wild mustard	1983	Ontario
32.	Solanum nigrum	black nightshade	1976	France
			1976	West Germany
			1979	Italy
			1983	Switzerland
			1984	Michigan
33.	Sonchus asper	spiny sowthistle	1981	France
34.	Stellaria aquatica (or Myosoton aquaticum)	water starwort	1983	Switzerland
35.	Stellaria media	common chickweed	1974	West Germany
			1983	Switzerland

Table 2

DISTRIBUTION OF TRIAZINE-RESISTANT MONOCOT (GRASS) WEEDS
(as of January, 1986)

	Genera	Species	Common Name	Year Found	Location
1.	Alopecurus	myosuroides	slender foxtail	1982	Israel
2.	Brachypodium	distachyon	false bromegrass	1981	Israel
3.	Bromus	tectorum	downy brome	1977	Nebraska
				1977	Kansas
				1977	Montana
				1978	Washington
				1978	Oregon
				1981	France
4.	Digitaria	sanguinalis	large crabgrass	1983	France
5.	Echinochloa	crus-galli	barnyardgrass	1978	Maryland
				1980	West Virginia
				1981	France
				1981	Ontario
				1982	Austria
6.	Lolium	rigidum	rigid ryegrass	1982	Israel
7.	Lophochloa	phleoides	?	1982	Israel
8.	Panicum	capillare	witchgrass	1975	Michigan
				1980	Ontario
9.	Phalaris	paradoxa	hood canarygrass	1982	Israel
10.	Poa	annua	annual bluegrass	1976	California
				1977	France
				1978	Belgium
				1981	Netherlands
				1982	England
				1983	Germany
				1983	Switzerland
11.	Polypogon	monspeliensis	rabbitfoot polypogon	1982	Israel
12.	Setaria	glauca	yellow foxtail	1981	France
				1981	Ontario
				1984	Pennsylvania
				1984	Maryland
13.	Setaria	viridis	green foxtail	1981	France

Table 3

OCCURRENCE AND DISTRIBUTION OF WEED BIOTYPES RESISTANT TO VARIOUS OTHER HERBICIDES
(as of January, 1986)

	Herbicide	Genera Species	Common Name	Year Found	Location
1.	Diclofop methyl	Lolium rigidum	Annual ryegrass	1982	Australia
2.	2,4-D	Daucus carota	Wild carrot	1962	Ontario, Canada
3.	Diuron	Senecio vulgaris	Common groundsel	1984	California
		Chlamydomonas reinhardi	(Algae-lab strain)	1976	Indiana
		Euglena gracilis	(Algae-lab strain)	1976	France
4.	Paraquat	Erigeron linifolius	Hairy fleabane	1979	Egypt
		Erigeron philadelphicus	Philadelphia fleabane	1981	Japan
		Hordeum glaucum	Wall barley	1983	Australia
		Poa annua	Annual bluegrass	1978	England
5.	Pyrazon	Chenopodium album	Common lambsquarter	1984	East Germany
				1984	Hungary
6.	Trifluralin	Eleusine indica	Goosegrass	1970	South Carolina

Table 4

HERBICIDES WITH HIGH RISK FOR WEED RESISTANCE

Herbicide Classification	Examples	
	Common Name	Trademark
1. Bipyridiliums	Paraquat	Paraquat
	Diquat	Diquat
2. Dinitroanilines	Trifluralin	Treflan
	Benefin	Balan
	Pendimethalin	Prowl
	Oryzalin	Surflan
3. Diphenyl ethers	Acifluorfen	Blazer
	Diclofop methyl	Hoelon
	Oxyfluorfen	Goal
4. Triazines	Atrazine	AAtrex
	Prometryn	Caparol
	Cyanazine	Bladex
	Prometon	Pramitol
	Simazine	Princep
	Metribuzin	Sencor
5. Uracils	Bromacil	Hyvar
	Terbacil	Sinbar
6. Ureas	Diuron	Karmex
	Fluometuron	Cotoran
	Linuron	Lorox
	Tebuthiuron	Spike

Table 5

HERBICIDES WITH LOW RISK FOR WEED RESISTANCE

Herbicide Classification	Examples	
1. Aliphatics	Dalapon	Dowpon
	TCA	Sodium TCA
	Glyphosate	Round-Up
2. Organic arsenicals	DSMA	Several
	Cacodylic acid	Rad-E-Cate
3. Acetanilides or Amides	Alachlor	Lasso
	Metolachlor	Dual
	Propachlor	Ramrod
	Diphenamid	Enide
	Napropamide	Devrinol
	Propanil	Stam
4. Benzoics	Dicamba	Banvel
	Chloramben	Amiben
5. Carbamates	Chlorpropham	Chloro IPC
	Phenmedipham	Betanal
	Asulam	Asulox
	Barban	Carbyne
6. Nitriles	Bromoxynil	Brominal
7. Phenoxys	2,4-D	Several
	MCPA	Several
8. Thiocarbamates	EPTC	Eptam
	Butylate	Sutan
	Diallate	Avadex
	Molinate	Ordram
	Vernolate	Vernam